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A PRELIMINARY STUDY OF AEROSOL INITIATED CO2 LASER PRODUCED AIR--ETC(U)

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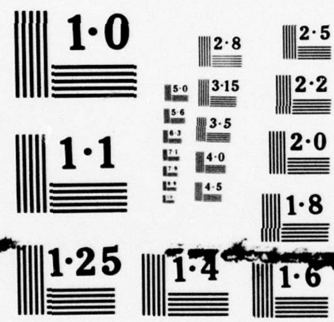

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NRL Memorandum Report 3647

A Preliminary Study of Aerosol Initiated CO_2 Laser Produced Air Sparks and Their Ability to Guide Electrical Discharges

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The time development of air sparks initiated on aerosols near the focal region (f = 3m) of a 1 kJ CO_2 laser beam has been studied. The spark at each aerosol produced a shock wave that expanded spherically at approximately 2×10^5 (200 000) cm/sec during the 1.5 μsec (microsec.) tail of the laser pulse. In time these spherical waves coalesced forming a turbulent cylindrical column from which a cylindrical blast wave separated. The turbulent cylindrical region was nearly stationary (> 100 μsec (microsec.) time scale) and was able to conduct electrical streamers at greatly enhanced velocities, → (Continues)		

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18. Supplementary Notes (Continued)

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20. Abstract (Continued)

($\sim 5 \times 10^8$ cm/sec) at times as long as one millisecond after the laser pulse.

5000 Km/sec

CONTENTS

A PRELIMINARY STUDY OF AEROSOL INITIATED CO_2 LASER PRODUCED AIR SPARKS AND THEIR ABILITY TO GUIDE ELECTRICAL DISCHARGES

I. Introduction

The effectiveness of aerosols in lowering the threshold intensity for laser radiation breakdown in air has been well established.[1,2,3] Particles in the size range of one or two microns reduce the breakdown threshold by an order of magnitude below experimental and theoretical[4] values obtained for particle-free air ($\sim 10^{10}$ watts/cm^2). Larger particles ($\sim$ 100 μm) and longer laser pulse lengths ($\sim$ 30 μsec) reduce the breakdown threshold[5] to as little as $\sim 10^6$ watts/cm^2. As a result of these aerosols, a high power laser and a long focal length lens are able to produce chains of laser breakdown sparks over distances up to 60 meters.[6,7] This report describes recent experimental data on the evolution of individual laser sparks into a cylindrical channel, and the ability of this channel to guide electrical discharges.[8]

II. Results and Discussion

The experiment was conducted as follows: A chain of laser sparks was produced by a one kilojoule CO_2 laser pulse[9] (100 nsec, FWHM, initial spike followed by a 1.5 μsec tail) that was focussed in air by a 3.0 meter focal length germanium lens (Figure 1). At a predetermined interval after the leading edge of the CO_2 laser pulse, the expanded beam from a Q-switched ruby laser (20 nsec half width) was transmitted

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through the chain of sparks near the focus of the germanium lens and recorded photographically, either as a Schlieren record or as a holographic interferogram. This region was also observed using time-integrated photography, fast-framing and streak photography, and emission and absorption spectroscopy. Individual aerosol initiated sparks were created where the incident laser power density was $\sim 10^8 W/cm^2$ in the spike of the laser pulse or $10^7 W/cm^2$ in the tail of the pulse.

Figure 2 is a set of Schlieren photographs taken at progressively later times after the initiation of the CO_2 laser pulse. The photographs show how the initial development of spherical shocks from many exploding aerosols evolved into a single cylindrical shock surrounding a nearly stationary core. For about the first 1.2 μsec, which was during the CO_2 laser tail, many of the individual sparks maintained their identity well enough to permit measurements of radius as a function of time.

There was a spread in the shock radii at any given instant, as shown in Figure 3, which indicates a spread in shock velocity or time of formation. With the single assumption that the time of formation varied up to ~ 200 nsec, which is consistent with streak and framing camera results, almost all of the measured spherical shocks can be plotted on the graph

$$r = A(\tau)^{.75}, \quad (1)$$

where A = 7000 in CGS units. In this expression τ, which is given by

$$\tau = t - \Delta t,$$

is the age of an individual laser spark, and Δt is the time after the beginning of the CO_2 laser pulse at which this spark is assumed to have

been created. The r-t relationship of Eq. (1) is very different from that of the spherical blast wave,

$$r \sim (E_o/\rho_o)^{.2}t^{.4},$$

where ρ_o is the atmospheric density and E_o is the shock energy, but is consistent with results obtained by Lencioni and his colleagues[1,2,5] both on large carbon particles and on glass fibers. (This same type of expansion, $r \sim t^{.8}$, was also observed by Daiber and Thompson[10] but under very different experimental conditions.) Eq. (1) implies that all the laser sparks expanded in a similar manner, and that during their expansion they absorbed energy from the tail of the CO_2 laser pulse.

As pointed out by Lowder and Kleiman[5] expansion with $r \sim t^{.8}$ implies that the energy contained in each laser spark varied as

$$E \sim \int_o^t q\ (t)\ dt \sim t^2$$

or

$$q(t) \sim t$$

where q(t) is the rate at which energy was being absorbed at time t. At the same time the nearly spherical expansion implies that the absorption was relatively weak and nearly constant around the surface of the sphere.

Interferometric holograms of these expanding spherical shocks are not readily analyzable. Because of the use of only a single wavelength (6943 Å), it is not clear whether fringe shifts were due to electrons or neutral molecules. Then, because of the smallness of the spheres, the sharp discontinuity at their surface, and the quality of the interferograms, there is uncertainity in the actual size of the fringe shift. Despite these limitations, the interferograms are in most cases, con-

sistent with the model of these expanding spheres as being a shell of increased density (several times atmospheric density) surrounding a region of reduced density. This model is consistent with the Schlieren data where at 1.2 μsec and 2.0 μsec a distinct shell can be seen around each laser spark ($R/\Delta R \sim 7$). [A plane shock in air with velocity 2×10^5 cm/sec would have a density behind the shock of $5\rho_o$ and temperature 2400°K.[11]]

Time-integrated emission spectra of the laser sparks show that they were of two distinct types. One has a continuous spectrum through the visible region, somewhat characteristic of a hot filament or carbon arc anode. The other shows a line spectrum characteristic of OII and NII. However, the lines in these spectra are rather broad (~ 1 - 4 Å). Presumably the latter spectra, although time integrated, relate to the sparks seen on the streak and framing cameras to last ≤ 0.2 μsec. Then the line broadening must have been due to plasma Stark effects[12] and indicates electron densities in the range $0.5\text{-}1 \times 10^{18}$ cm^{-3}. The electron temperature must have been several electron volts to produce the observed first ion spectra. The continuous spectrum, on the other hand, may be indicative of a low level of light emitted over a much longer time scale (perhaps milliseconds) characteristic of glowing solid particles which have frequently been seen in this type of experiment.[2,13]

Detailed comparison of the aerosol initiated laser sparks with theory[14] is difficult because we do not know the actual laser intensity at different positions along the spark chain. Calorimeter measurements show that approximately 20% of the laser energy was transmitted through the chain of sparks. But streak camera records of the luminosity of

the sparks (Figure 4), show that although breakdown occurred immediately ($< 10^{-7}$ sec) in the region near the focus (i.e., where records shown in Figure 2 were taken), breakdown did not occur until after the initial laser spike at places > 30 cm away from focus. Another unusual feature of this experiment is that because the laser beam was large (focal spot diameter ~ 2 cm) the expanding laser sparks were always fully bathed in laser radiation. Thus radiation thresholds[14] caused by loss of plasma (energy) out of the laser beam do not apply.

It is perhaps interesting to reverse the process and observe that the measured radial velocities ($\sim 2 \times 10^5$ cm/sec) when equated to the Raizer velocity[14,15] correspond to laser intensities of $\leqslant 10^6 W/cm^2$ if we use a value of $\gamma = 1.33$ for air.[16] Bearing in mind that the power density in the Raizer formula is that absorbed, this value is consistent with the estimated laser intensity in the focal region after allowing for ~ 80% absorption of $2 \times 10^7 W/cm^2$ during the tail of the laser pulse.

Despite the differences between the two experiments there is a great similarity between the interferometric and shadowgraph results presented by Maher and Hall[17] from laser/solid target interactions and our own results. In particular results presented in Figures 13, 14, and 15 of Reference 17 are very comparable to similar data for individual aerosol initiated laser sparks. Also the peak electron density measured in their "laser induced shock waves" ($\sim 10^{18}$ cm^{-3}) is similar to that indicated by the time integrated spectroscopy.

At t = 2 μsec the expanding spherical waves began to coalesce and form a cylindrical column from which a cylindrical shock wave subsequently separated (Figure 2). Since the CO_2 laser power had decayed to

zero by this time it is assumed that this cylindrical wave was a blast wave. At $t = 50\ \mu sec$ the cylindrical blast wave ($M = 1.3$) was well separated from a central core, containing Schlieren features similar to those of the turbulent wake behind an object in a supersonic wind tunnel. (See for example, the Schlieren photographs in Reference 18). Interferograms of the core show a complex fringe pattern that does not permit the symmetry assumptions usually made to compute index of refraction. Thus our only information so far on this core is that it remained stationary from 10 μsec to at least 100 μsec after the firing of the CO_2 laser. It was clearly a region of reduced density and increased temperature and was in pressure equilibrium with the atmosphere around it. Interferograms at $t = 50\ \mu sec$ show that the density jump across the cylindrical blast wave was consistent with that calculated for an air shock[11] at mach 1.3, and indicate that the pressure around the stationary central core did not appreciably exceed atmospheric pressure, which is to be expected for a simple blast wave.[19]

An attempt was made to observe the presence of readily ionizable molecules, in particular O^- ions, in this central core. This was done using absorption spectroscopy over the range 2500 A^o to 8500 A^o. The background light source was a small xenon filled high pressure flash lamp with a time duration of ~ 5 μsec. This lamp was bright enough and the collimation good enough that light emission from the luminous sparks did not register on the films when absorption spectra were being recorded. No absorption (bands, lines or edges) was observed throughout this region at any time from 0 to 100 μsec after peak CO_2 laser power. Therefore we believe the O^- concentration throughout this period remained

below ~ 10^{13} ions/cm^3.

An investigation was made into the ability of these laser spark chains to enhance streamer propagation and guide electrical discharges. As shown in Figure 5, this was accomplished by focussing the CO_2 laser through 5 cm diameter holes in each of two parallel, planar electrodes, producing a chain of laser sparks between them. A 360 kV Marx generator pulse was then applied across the electrode gap (0.5 meter) at varying time intervals after the laser was fired. The results were as follows: With no laser sparks between the electrodes, the high voltage arced to the Marx generator case, approximately 2 μsec after the application of the voltage pulse. When laser sparks were created between the electrodes, the high voltage arc was guided to the ground electrode along the path of the laser, as long as the voltage was applied less than 2 msec after the laser pulse. If the high voltage was applied less than one millisecond after the CO_2 laser was fired, the streamer propagation time between the electrodes was less than 100 nsec. In this time the Marx generator reached only a fraction of its full voltage. There was a qualitative difference between the electrical discharges that were initiated less than 500 microseconds after the CO_2 laser pulse, and those that were initiated a millisecond after the laser pulse. In the former case many parallel individual discharges were propagated, each "hopping" more or less randomly, from spark to spark between the electrodes. In the latter case, the individual sparks seem to have lost their identity and the discharge propagated along a single generally straighter path possibly defined by the stationary core seen in the Schlieren and the interferometric data.

III. Conclusion

The hydrodynamic development of breakdown sparks produced by a

focussed CO_2 laser beam has been studied using Schlieren photography, interferometry, framing and streak photography, and spectroscopy. These "sparks" have been shown to be spherically expanding shells of air plasma or in some cases possibly just glowing aerosols. The former are weakly absorbing laser supported shock waves, which grow until they coalesce to form a cylindrical channel. These waves are very similar to the laser supported waves seen by other workers on single large carbon particles[2], glass fibers[5], and even solid targets[17].

It has also been demonstrated that the chain of breakdown sparks is capable of guiding electric discharges for periods up to two milliseconds after the laser pulse. In these experiments the presence of the chain of laser sparks not only enhanced the streamer velocity from $\sim 2 \times 10^7$ cm/sec (unguided) to $\geqslant 5 \times 10^8$ cm/sec (guided), but actually guided the discharge along a completely different path from that taken during unguided breakdown.

In future work, we shall endeavour to understand more of the atomic physics governing these aerosol initiated laser produced air sparks; to ascertain the different effects on electrical guiding of small hot aerosol particles and laser produced air sparks; to understand the mechanisms limiting the time duration of the guiding phenomenon; and to extend the guiding of electrical discharges to lower average field strengths (presently 7.2 kV/cm).

IV. <u>Acknowledgment</u>

The authors gratefully acknowledge the assistance of Michael Raleigh and Edward Laikin in these experiments.

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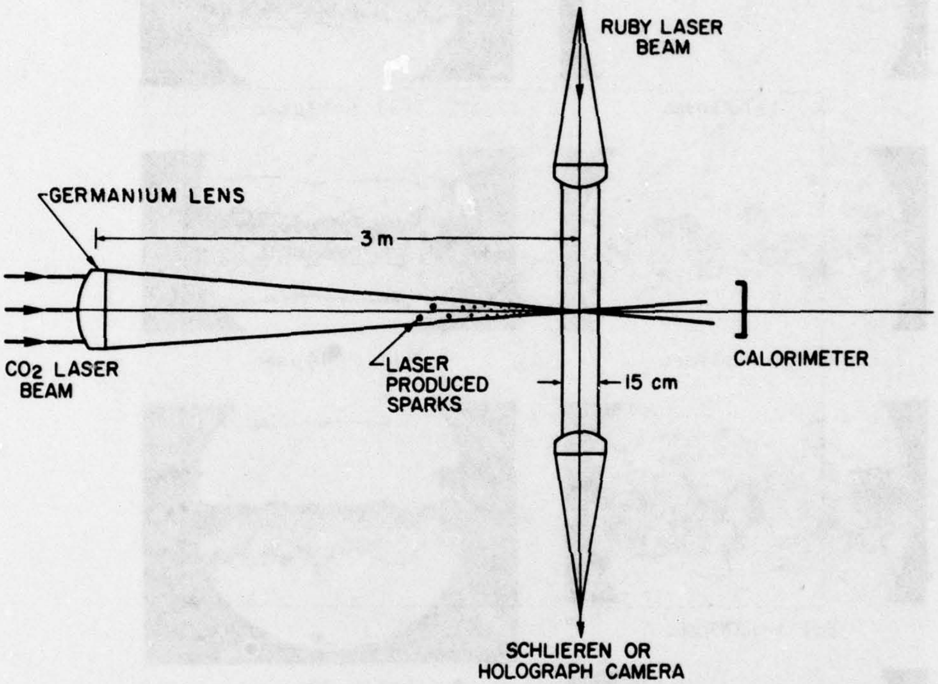

Fig. 1 — A schematic diagram of the laser spark experiment

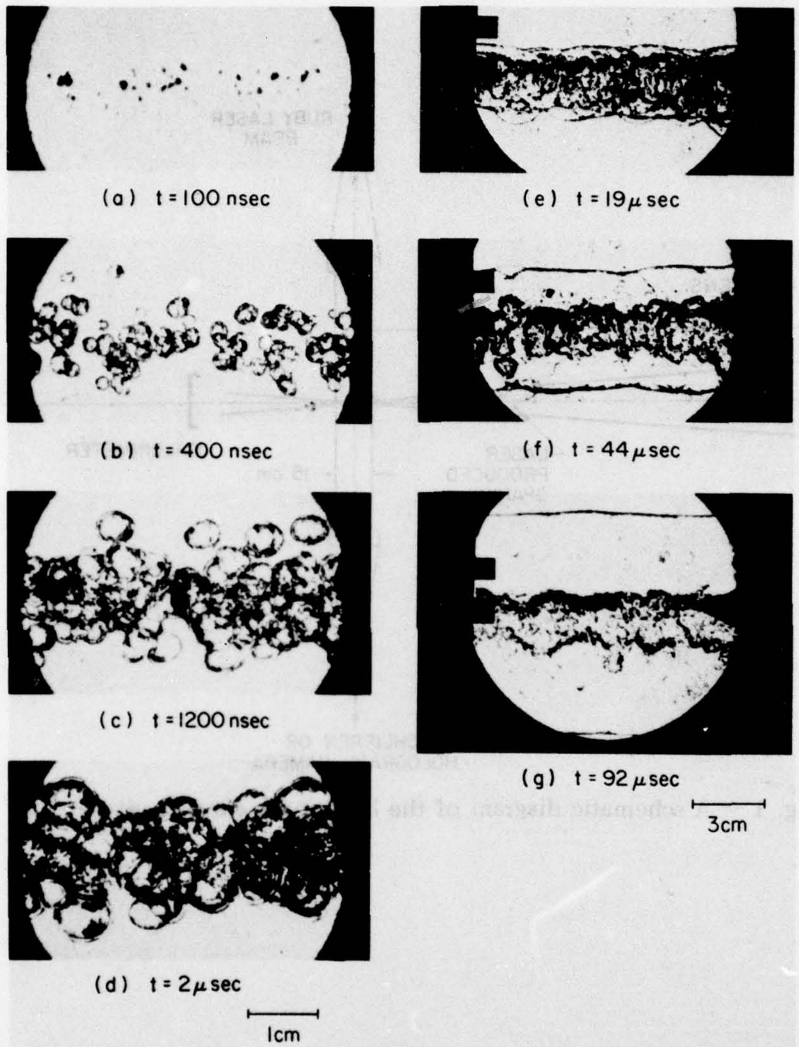

Fig. 2 — Schlieren photographs showing the development of laser spark generated shock waves. Pictures a-d are of the same scale, as are pictures e-g. Time is measured with respect to the leading edge of the CO_2 laser pulse.

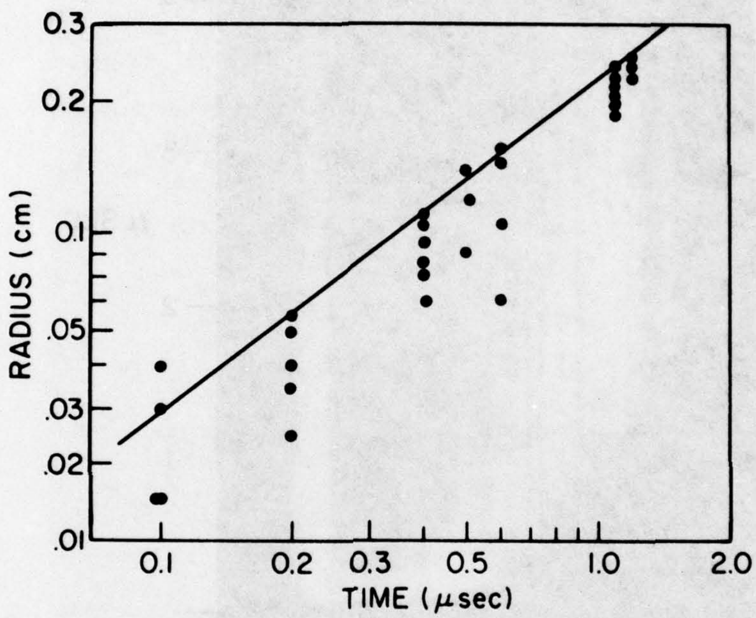

Fig. 3 — This graph is the result of measuring the radii of the spherical shock waves recorded on Schlieren photographs taken at different times after the leading edge of the CO_2 laser pulse. The solid line, $r = 7000\ t^{.75}$, represents the upper limit of the radial expansion as a function of time.

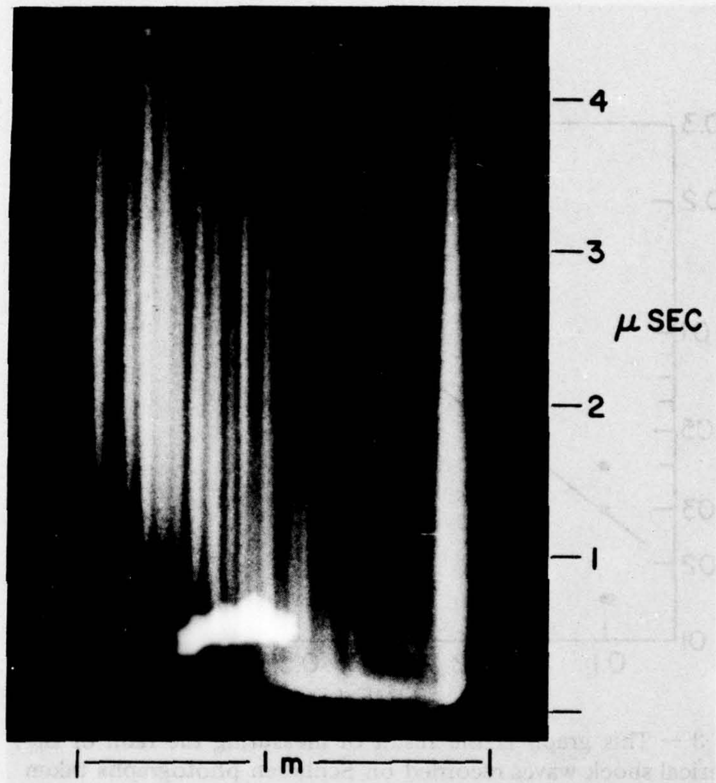

Fig. 4 — A streak camera record of the self luminosity of the laser produced sparks in air. The focused CO_2 laser beam is incident from the left and strikes an aluminum plate at focus on the right.

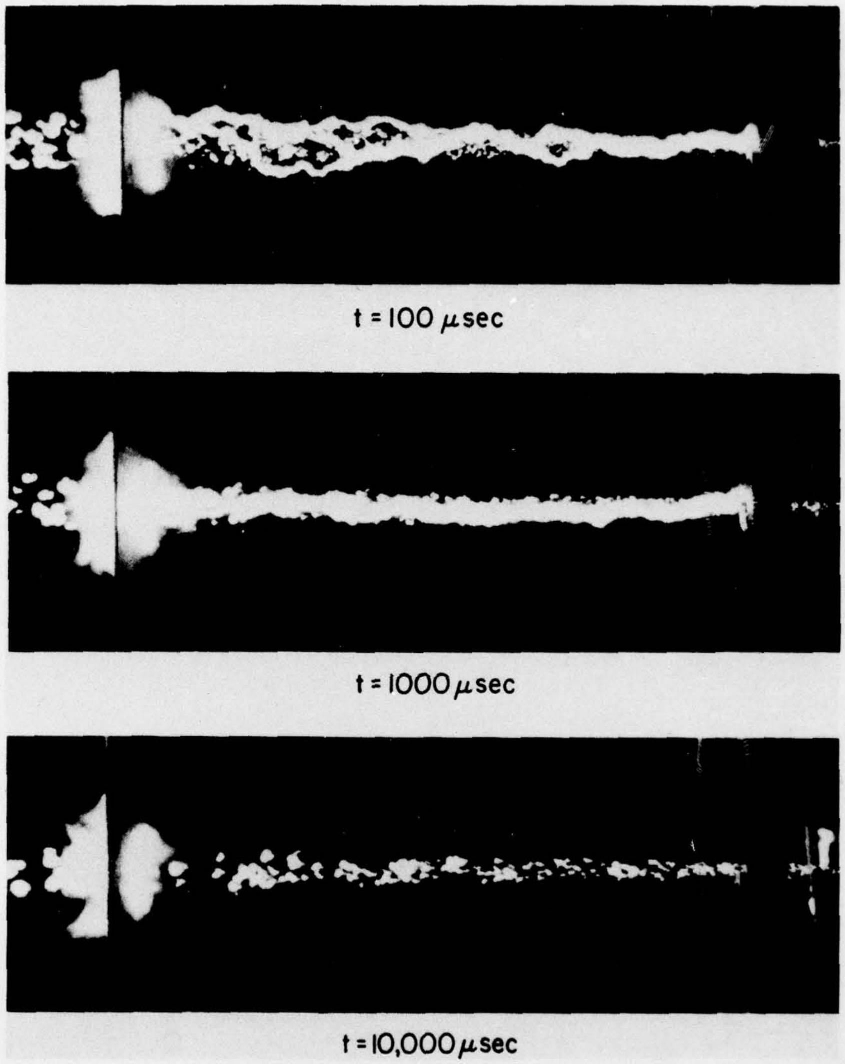

Fig. 5 — Still-camera photographs of laser guided sparks. The laser is incident from the left. The electrode spacing is 0.5 m, and the high voltage electrode (positive) is at the right. The values of t are the intervals between the CO_2 laser pulse and the application of the high voltage. In the last photograph, the arc did not follow the laser spark chain, but jumped to the nearest ground point, which was less than 40 cm from the high voltage electrode. This breakdown path can be seen in the right hand side of the photograph.